met.lbl.gov Documentation

Prepared by Chris Anderson
Last updated 2021.03.08 see Changelog for updates

Experiment Essentials

What you provide for each shift

All resist, underlayer, and non-standard developer materials

- They arrive at least three business days before your shift
- Information about each package/sample needs to be uploaded to this website on the experiment page.
- All materials must be shipped in a ready-to-use state. *We generally don't perform dilutions, mixing, weighing, or any alterations of your materials. But if it's what you need for your research, we have an open mind.*

An experimental plan

Used by our operators to carry out the experiment per your instructions. For each wafer, it specifies:

- Underlayer process (UL name, suggested RPM, desired thickness, acceptable thickness tolerance, PAB)
- Resist process (resist name, suggested RPM, desired thickness, acceptable thickness tolerance, PAB, PEB)
- Post process (PEB, Develop, rinse, hard bake)
- Reticle + field + target feature (the target feature is important so we can correctly center the illumination).
- Illumination coherence (pupil fill)
- Target dose, dose step size, number of dose steps
- Focus step size, number of focus steps

What we provide for each shift

1. Support and assistance for planning the experiment
2. Coating and processing of all materials
3. Si wafers
4. HMDS
5. TMAH 2.3 wt. % developer. 2-Heptanone developer/rinse
6. Multi-purpose reticle for imaging
7. Operation of the litho system
8. Support/assistance for custom processing and/or custom exposures. Please contact Patrick or Chris for assistance.
9. SEM (Hitachi S-4800) access for users with guest status; however, we reserve the right to use the SEM intermittently for the purpose of providing dose + focus feedback to MET operators.

Shift hours

- Owl: 00:00 - 08:00
- Day: 08:00 - 16:00
- Swing: 16:00 - 24:00

Scheduling / Shift Allocation

MET shifts are generally allocated in six-month blocks, every six months, but this sometimes varies. We do our best to make sure each member company receives the same number of day, swing, and owl shifts. If you have special needs or requests, please contact our technical staff.

Productivity / How Many Wafers Should I Put on The Shift Plan?

A good rule of thumb is three to five. Here is our recommendation:

- estimate how long it would take you to manually coat + PAB + measure all underlayers
    - include time for coating HMDS
    - Include time for figuring out spin speeds if you don't provide them
    - Include time for bake plates to come to temp / cool if you require changes (we have four plates total so use best judgement)
- Estimate how long it would take you to manually coat + PAB + measure all resists
    - Include same time factors listed above
- Estimate how long it would take you to manually PEB, dev, rinse, hard bake all wafers
- Assume 1.25 hours per wafer for litho set-up and exposure.
- Assume everything happens serially, e.g.,
    - Wafer1: coat UL → coat resist → litho → post →
    - Wafer2: coat UL → coat resist → litho → post → and so on
    - In reality some litho / coating happen in parallel, but it is hard to time things ideally since everyday is something new for us. We almost always end up with some serial execution so serial is a good assumption.
- If you want to add SEM checks between wafers to get dosing or focus information for the next experiment, add time for that too.
- Fill up 7 hours worth of time.
    - We reserve 1 hr of every 8-hr shift to set up the litho system and expose the calibration wafer and examine it in the SEM to validate the health of the litho system.
- If you follow all of the above rules of thumb, three to five wafers is probably what you will end up with, depending on your specific particulars.
- Things that can improve productivity:
    - Tell us pre-determined spin speeds for all materials
    - Ship us pre-coated wafers (yes some customers do this!)
    - Perform complex processing steps in-house (coat or post)

Some customers provide more wafers in the plan than is probable to accomplish in a single shift. The rationale here is "never waste photons". We get that. And feel free to. Just know we don't look at a seven-wafer-plan and decide to change how we work vs. a two-wafer-plan. You'll get the same consistent output from our workers every shift regardless of the size or complexity of your plan. Some of the shifts may give you two wafers, some four, some six.

How we define a successful shift

We feel we have fulfilled our obligation to you when:

- Our equipment is functioning properly
- Our staff is working competently attempting to execute your experimental instructions
- We are accurate, transparent, and rigorous in our attempt to execute your instructions.

These things don't factor in:

- Number of instructions/tasks completed.
- Complexity or simplicity of what you are asking for.

We don't have any productivity or throughput guarantees for shifts and we don't think in terms of "you get X wafers per shift". Our commitment to you is to show up every day well-rested, clear-headed, and ready to carry out your experiments with as much attention to detail and care for the research as you would. Our goal is to carefully execute your instructions, pay attention to every detail, and work at a pace where we can minimize mistakes. We make sure we get things right, and ship wafers we are confident in.

We would love for every day to be predictable enough that we could confidently say "you get X wafers per shift". But in practice, we've found that trying to meet a throughput target doesn't lead to maximizing value to our customers. In fact, it tends to have the opposite effect.

We encourage users to think bigger than a single 8-hr shift. Instead, think in terms of a quarter or a year and within the larger context of your research goals. E.g., you may not get result B this shift, but we will get to it your next shift. It works best if at any given time, you have a dozen or so wafers or so in mind and accept a fluid timeline for when you'll get the results. If things go exceptionally well, we maybe can knock out 12 wafers in two shifts. If your experiments are more challenging, maybe it takes four shifts, or five. Building in some flexibility from the start in your expectations is helpful. As new results come in, you can start adding more to your research queue.

How we define an unsuccessful shift

- The equipment is down / malfunctioning longer than 4 hours **OR**
- The team is unavailable or at heavily reduced capacity for more than 4 hours.

Am I charged for an unsuccessful shift?

No. You will be credited. We round to a full shift because it is the easiest way for us to track and issue credits.
Examples:

Situation	Shift Status	Credit issued
Litho system malfunctioning 2 hours.	fulfilled	No
Litho system malfunctioning 5 hours	unfulfilled	Yes
Track down for 3.5 hours	fulfilled	No

Experimental Plan Template

The experimental plan is your prioritized list of instructions for our team during the shift. Here is an example.

- Example Plan (Excel)
- Example Plan (Google Sheets)

As described in the Productivity / How Many Wafers can I get Exposed In a Shift? Section, we view the experimental plan is a prioritized set of instructions and we don't view it as:

- a list of things we are required to complete
- a list of things we guarantee to finish

Submitting Experimental Plans

- Experimental plans get uploaded through this website on the My Shifts detail page before the shift. If you need to make revisions after you submit a plan, upload another plan and we will use the most recent one.
- Each experimental plan is accompanied by a discussion thread that allows you to communicate with MET technical staff regarding your plan. Please use this instead of email for all plan-related correspondence.

Providing resists, underlayers, and developers: Overview

You are required to provide all resist, underlayer, and development materials for your shifts (with the exception of MF-26A developer and 2-Heptanone developer).

All materials should be shipped in a ready-to-use state. *We generally don't perform dilutions, mixing, weighing, or any alterations of your materials. But if it's what you need for your research, we have an open mind.*

Volume for 200 mm Wafers for MET5

For each material, please ship 2 mL per wafer plus 10 mL "overhead". "Overhead" gives us 6 mL to use for determining spin speed and 4 mL for rework. Examples:

- If your plan has four wafers that all use the same material, ship us at least 18 mL of that material (2 mL * 4 + 10 mL overhead)
- If your plan has four wafers that each use a different material, ship us at least 12 mL of each material. (2 mL + 10 mL overhead) for each.

Volume for 100 mm Wafers for DCT

We manually use a pipette to withdraw resist out of the bottle and apply it to the wafer. Our 4" wafers require about 1 mL to coat the wafer. There should be enough material for all of your wafers and a bit extra for test wafers to dial in the correct spin speed. In general, materials should be shipped in the smallest volume that is required by the experiment so excess waste is avoided.

Shipping: Ensure arrival three business days prior to shift

Our receiving department has an average of a 2-day "hold" on most packages. For example, if your package arrives at LBNL on a Tuesday, we most likely will not see it in our lab until mid day on Thurdsay. For this reason, your packages need to arrive at LBNL a minimum of three (3) business days before your shift. Earlier is even better.

Shipping: Adding contents / tracking information to met.lbl.gov

When shipping materials to LBNL, each physical package you ship needs to be submitted on the "My Packages" page. Here is a summary of the process:

1. Click the "add package" button and follow the instructions on the subsequent page.
2. After uploading the package information, it will show up on the My Packages page and you will receive an email with the shipping address
3. Repeat this for every package you ship
4. When you receive tracking information for a package, add it on the "My Packages" page (there will be a "add tracking number" button)
5. When we receive the package we check it in and notify you via email. Samples that are received will look like this:
    - Resist A ✓ received
    - Resist B ✓ received
6. Samples that were supposed to be in the package, but were not found, look like this:

    - Resist C ⌀ missing
    - Resist D ⌀ missing
7. 30 days after your shift, you will recieve an email that says we will dispose all of the samples from the shift. At this point, you will have the option to transfer some of the samples to your next shift. See "Moving material to another shift, below".
8. Samples that are disposed (not transferred) will look like this once our staff disposes them:
    - Resist A ✓ received
    - Resist B ✓ received

If someone other than you ships a package for your shift it is your responsibility to make sure the package information is entered into this site.

Shipping: Packaging and Labeling Instructions

Hazardous materials need to be packaged to protect it from damage and to contain leaks, and to communicate information to the public. To achieve these goals, packaging needs to include:

Primary receptacles with Positive Closure and Label

- Leak tight for liquids and sift proof for solids
- Securely closed
- Marked with the full, non-abbreviated common name of the hazardous materials (equivalent methods may be used for primary receptacles that are too small for this)

Secondary containers must be used

To help contain spills and leaks from the primary receptacles, you must use secondary containers (often these are plastic bags).

Figure: Secondary containment for spills and leaks

Outer packaging that is:

- Packaged to secure the primary receptacles against shifting and protect it from damage
- Equivalent in strength and integrity to the manufacturer's original packaging
- Marked with the full, non-abbreviated common name of the hazardous materials
- As a best practice, staff should also label the receptacles with the owner and recipient's name and number
- In addition, sufficient (non-reactive) absorbent materials should be included in the outer packaging to absorb the entire contents of the primary receptacles should a spill occur

Outer packaging is not required if the primary receptacles are secured against shifting in cages, carts, bins, boxes or compartments.

Primary receptacle with positive closure and label

Secondary containment for spills and leaks

Outer packaging *(image is lacking absorbent material)*

Hand-delivering materials

Add one package and add all of the samples to this single package. Since there is no tracking number for hand-delivered packages, leave a comment that says "Hand delivered" and tells us the approximate time you will deliver the samples

Borrowing materials from another user

Occasionally, you may want to arrange to use materials owned by another MET user. Please follow these instructions if you want to do this:

1. Contact the owner of the materials to receive their approval.
2. Have a representative from the owner of the materials contact us to let us know that you are authorized to use their materials.
3. Please email us ahead of time with the names of the materials you want to use. We will check to make sure that the materials are in stock and send you a confirmation email.

Outbound shipments: How we ship you your exposed wafers

If you do not attend your shift, we can ship your wafers to you after your experiment. This is not automatic - you need to indicate that you want your wafers shipped for every shift. To this, scroll down to the "Outbound Shipments" section of the shift page and follow the on-screen instructions.

200 mm Wafer Processing Equipment

Sukudo/Screen SK80EX Overview

• 200 mm wafers • H20-based processing • Non-H20-based processing • 4 hot plates (250C max) • 2 chill plates • 1 HMDS (vapor) (unused as of 2021.02.12) • JA Woollam Ellipsometer for film thickness	

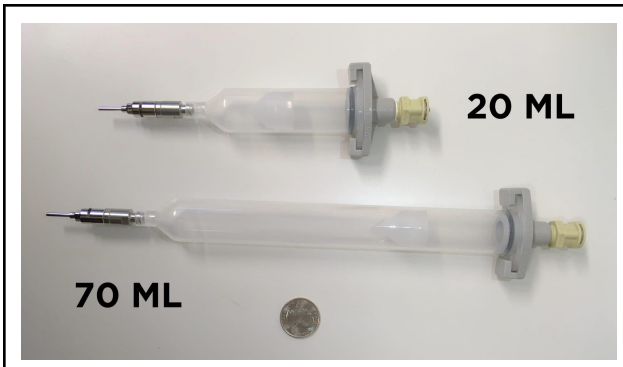
H20-Based-Processing with SK80 Track

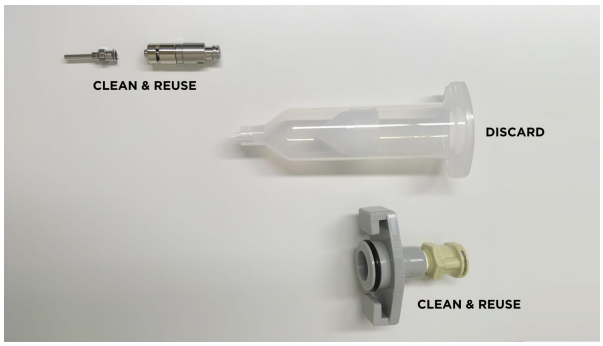
- Plumbed TMAH 2.3 wt. % in H20
- Plumbed DI H20
- Plumbed Surfactant Rinse (TBD)
- Spare Plumbed Aqueous Developer
- Manual Syringe dispense for everything else

Non-H20-Based Processing With SK80 Track

- Plumbed 2-Heptanone (Develop or pre-wet)
- Plumbed 70/30 PGME/PGMEA for bowl rinse, edge bead removal, back side rinse, pot rinse
- Automated syringe dispense for everything else like user resists, underlayers
- Split drain for material compatibility

Syringe Photos for SK80 Track

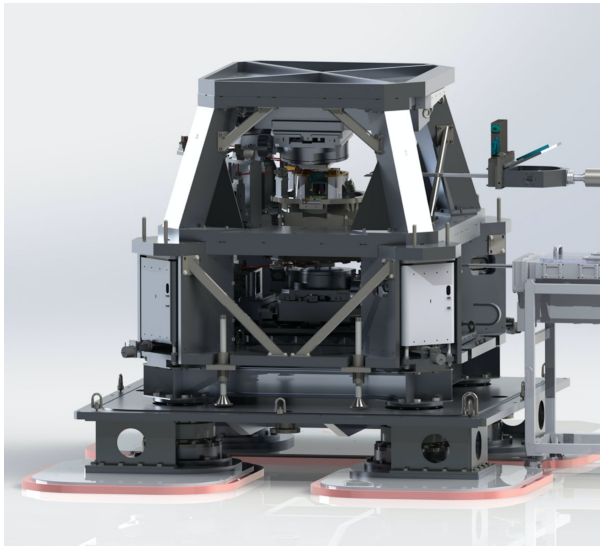




0.5-NA Patterning (MET5)

MET5 Overview

NA	0.5
Resolution	8 nm theoretical max (9 nm demonstrated SPIE 2020 in MOx)
Field Size	200 um x 30 um
Wafer Size	200 mm
Illumination	Custom pupil shaping (see more below)



MET5 Commissioning and Qualification Data

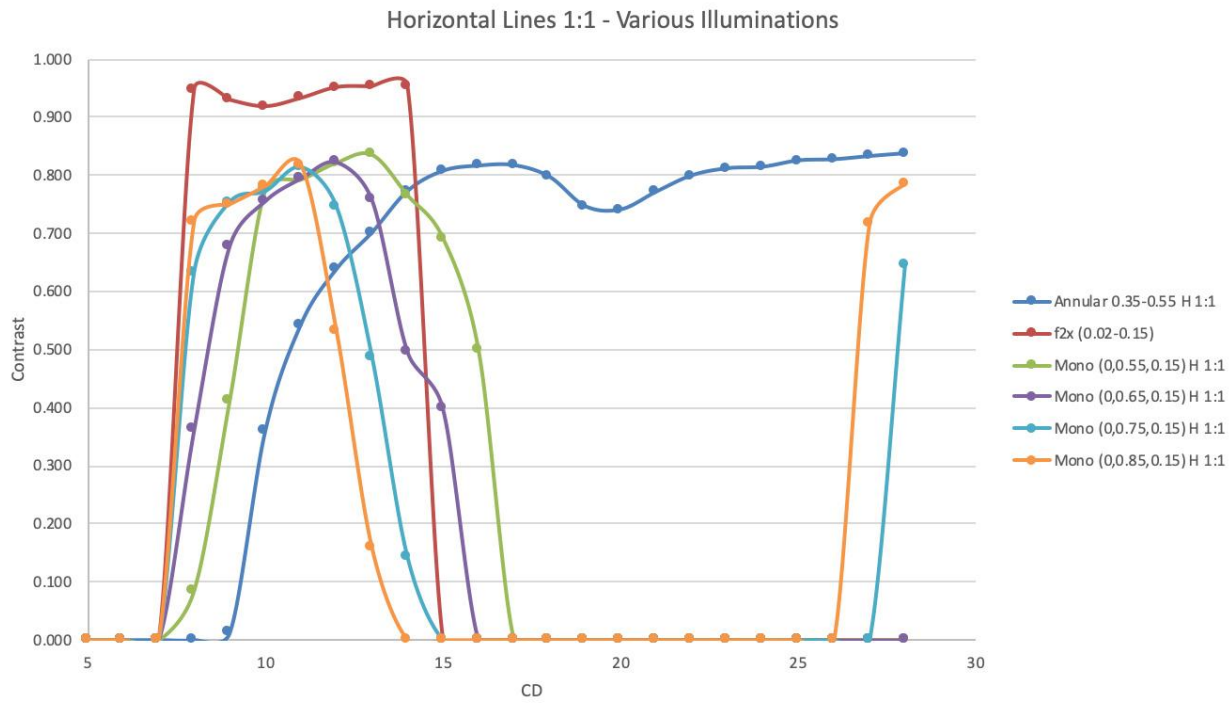
The 2019 MET5 SPIE Manuscript (PDF Pre-Release) and 2019 MET5 SPIE Presentation (PDF) include detailed commissioning and performance information. Here is a summary of commissioning results as of March 1 2019:

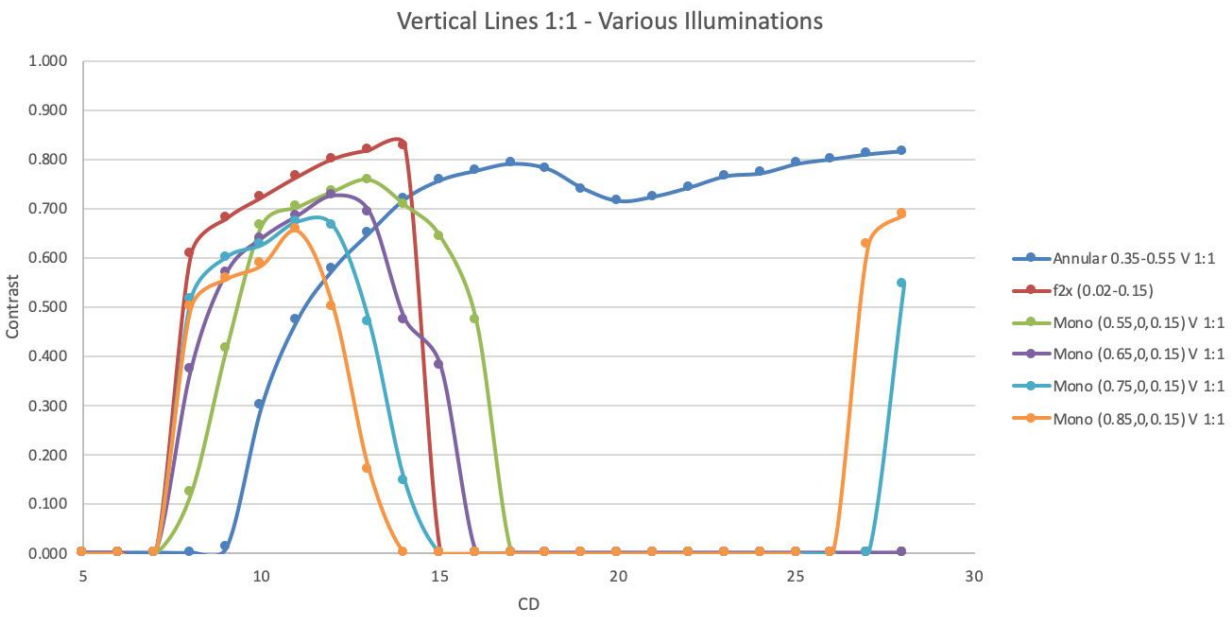
- patterning resolution of 13 nm half-pitch with annular 0.35 – 0.55 illumination

- patterning resolution of at least 10 nm half-pitch with annular 0.1 – 0.2 illumination (frequency doubling). For 9 nm half-pitch and 8 nm half-pitch, metrology is nearing the performance limit of the SEM. It is difficult to judge if the resist is fully resolved to the Si substrate or if the resist is a bulk block with sinusoidal thickness modulation.
- critical dimension (CD) uniformity of 0.7 nm 1σ on 16 nm nominal CD across 80% of the 200 um x 30 um aberration corrected field of view. Expect this across 100% of field by April 1
- aerial image vibration relative to the wafer of 0.75 nn RMS. Logged for every exposure.
- focus control and focus stepping of 15 nm (three steps through the depth of focus).

MET5 Aerial Image Contrast Modeling Data

This Excel file contains modeled aerial image contrast of dense lines and contacts for various illuminations in MET5. Here are a few summary contrast transfer functions. You are welcome to generate your own from the Excel data. This information may be updated and refined in the future. Table 1, below, copied from the 2019 SPIE Manuscript, shows the configuration of Hyperlith lithography simulation software used in these simulations.




Vertical Lines 1:1 - Various Illuminations
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Contrast
5
10
15
20
25
30
CD
Annular 0.35-0.55 V 1:1
f2x (0.02-0.15)
Mono (0.55,0,0.15) V 1:1
Mono (0.65,0,0.15) V 1:1
Mono (0.75,0,0.15) V 1:1
Mono (0.85,0,0.15) V 1:1

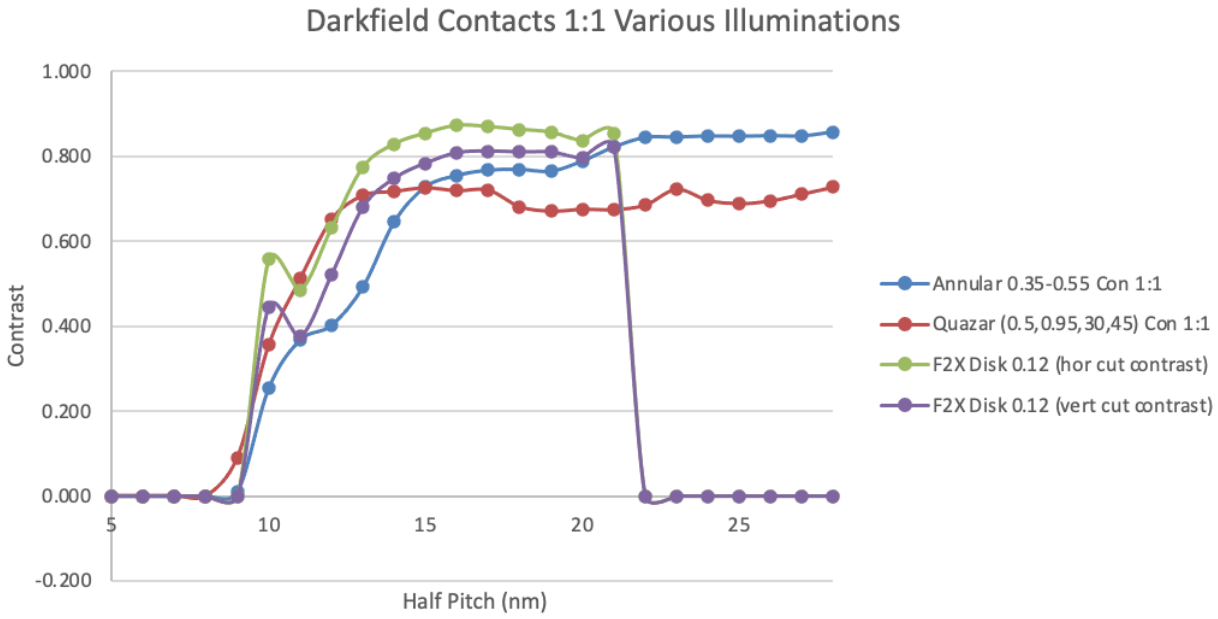

Darkfield Contacts 1:1 Various Illuminations
1.000
0.800
0.600
0.400
0.200
0.000
-0.200
Contrast
5
10
15
20
25
Half Pitch (nm)
Annular 0.35-0.55 Con 1:1
Quazar (0.5,0.95,30,45) Con 1:1
F2X Disk 0.12 (hor cut contrast)
F2X Disk 0.12 (vert cut contrast)

Table 1: Configuration of Hyperlith lithography simulation software for calculating the aerial images of 1:1 vertical lines in MET5 with annular 0.35 – 0.55 illumination

Mask	Multilayer	Mo/Si; d-spacing = 6.95 nm; gamma = 0.4; capping = 2 nm Ru
	Absorber	55 nm of TaN topped with 7 nm of TaON (a DUV antireflection coating)
	Optical Proximity Correction	None
Illumination	Wavelength	13.5 nm
	Polarization	Linear X
	Pupil Fill	Annular 0.35 – 0.55
Projection Optics	NA	0.5
	Central Stop	Sigma = 0.3
	Aberrations	0.29 nm RMS as measured with in-situ Lateral Shearing Interferometer
Field Point		Central

MET5 reticle/field layouts

- IMO410298 MET5 Field Layout (Oct 18 2020 - Present)
- IMO389285 MET5 Field Layout (July xx 2020 - Oct 18 2020) (has unintentional left-to-right flip relative to previous field assignment)
- Samsung MET5 Field Layout (Oct 2019 - July xx 2020)
- IMO261711 MET5 Field Layout (Commissioning - Oct 2019)

The MET5 default reticle provides a variety of general-purpose features. The MET5 reticle reliminary overview / description provides a high-level summary of the fields. High-resolution PDFs of select fields can be downloaded below (BF = bright field; LFBF = low-flare bright field; DF = dark field):

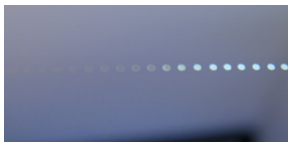
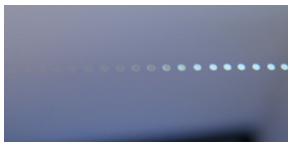
- Hexagonal Contacts BF | Field map no DF PDF available, but it is on mask.
- Contact Bias BF | DF
- F2X Cleave DF
- F2X Contact DF
- F2X DF
- F2X Aberration Monitor DF
- Illumination Monitor BF | BF on 40 nm grating

- Contact Bias Split BF | DF
- Contact Cleave 1:1 BF | DF
- Contact Cleave 1:6 BF | DF
- Line End And Distortion BF | DF
- Line/Space Bias Split BF | DF
- Line/Space Cleave BF | DF
- LBNL Aberration Monitor BF | DF | Local BF
- ASML Module 2 (private to LBNL)

Dose Calibration Tool (DCT) Features & Benefits

The Dose Calibration Tool (DCT) has an upstream tip/tilt stage that can rapidly scan the source beam in a grid during the exposure, improving uniformity across the field for a tradeoff in throughput (diagrams below the table). The following table shows the productivity of the DCT in the three available scanner / aperture configurations. The default configuration of the instrument is with the 500 um Ø aperture and the scanner off as this is the highest productivity configuration.

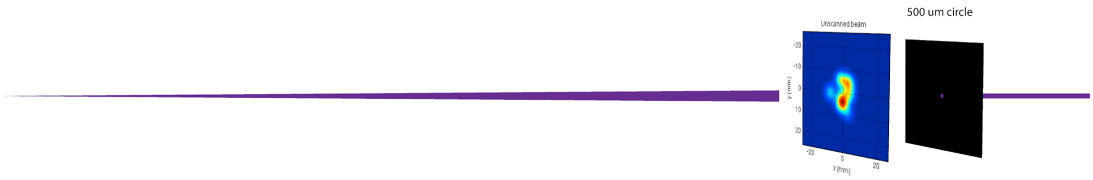
Three available scanner / aperture configurations

Configuration	**Default**	**Optional**	**Optional**
Aperture	500 um	500 um	1 cm x 1 cm
Scanner	Off	On	On
Wafer Pic			
Productivity	6 wafers/hour* • @ 10 mJ/cm^2 center dose • @ 50-point contrast curve See DCT calculator	4 wafers/hour* • @ 10 mJ/cm^2 center dose • @ 50-point contrast curve	4 wafers/hour* • @ 10 mJ/cm^2 center dose • @ 6-point contrast curve
Intensity Variation Across Field	39% PV Spec for central 400 um ⌀ of 500 ⌀ field Intensity variation often directional; caused by a circular	11.7% PV Spec for central 400 um ⌀ of 500 ⌀ field	11.7% PV Spec for central 8 mm x 8 mm of 10 mm x 10 mm field See 1 cm x 1 cm Clear-Field EUV

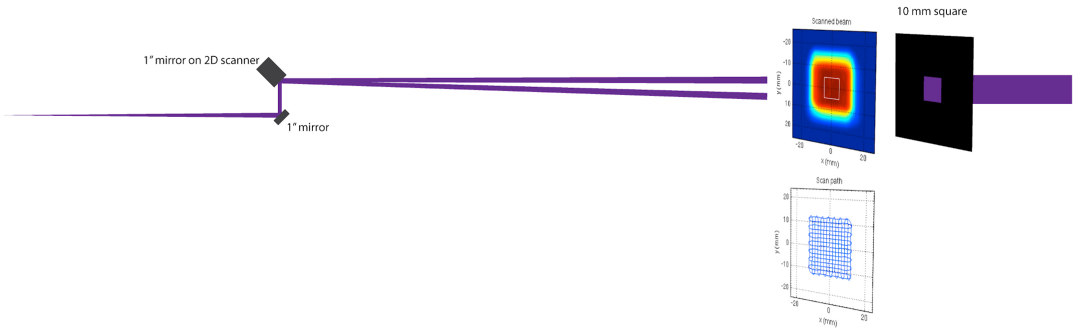
	aperture in a Gaussian beam. Intensity profile can change day to day due to small movement of ALS beam relative to aperture		Exposures With 1.8% RMS Intensity Variation for more more information

*Assumes a stack of pre-coated wafers is sitting there ready for the exposure system and that there are no extra processing steps outside of a 60 sec PAB, 60 sec PEB and 30 sec develop with TMAH.

DCT Scanner Off Diagram



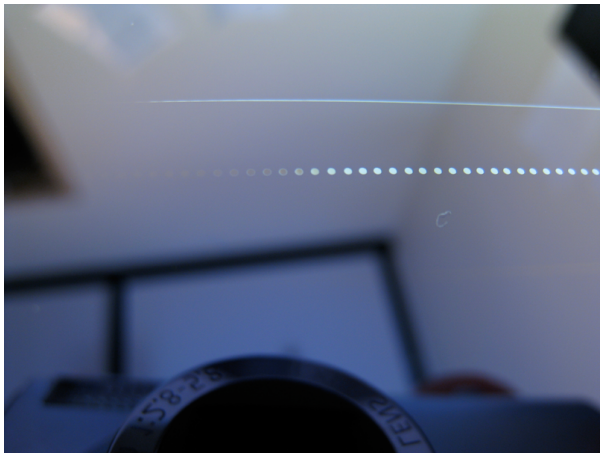
DCT Scanner On Diagram



DCT Minimum Dose = 0.3 mJ/cm^2

The DCT delivers a flux of about 6 mJ/cm^2/s (scanner off). The minimum reliable exposure time of the shutter is about 50 ms. This puts the minimum dose at 6 mJ/cm^2/s * 0.05 s = 0.3 mJ/cm^2. If you need to go lower than this, we can intentionally throttle back the flux of the DCT by adjusting the Advanced Light Source parameters but it would be a good idea to mention this in the comments on your shift page in advance so the operators are aware. We don't regularly go this low in dose so it would be out of the ordinary.

DCT Wafer Picture



Berkeley Lab Administrative Documentation

ALSHub accounts are Required (separate from met.lbl.gov account!)

All remote and attending users of the Berkeley MET facilities are required to have an ALSHub account. To create an ALSHub account, go to https://alshub.als.lbl.gov and scroll to the "create an account" section and follow the instructions. Once your ALSHub account has been created, email wholcomb@lbl.gov to let Warren know this is done.

You will not be able to use MET shifts until you have an ALSHub account.

LBL Address

1 Cyclotron Road
Berkeley, CA 94720 USA

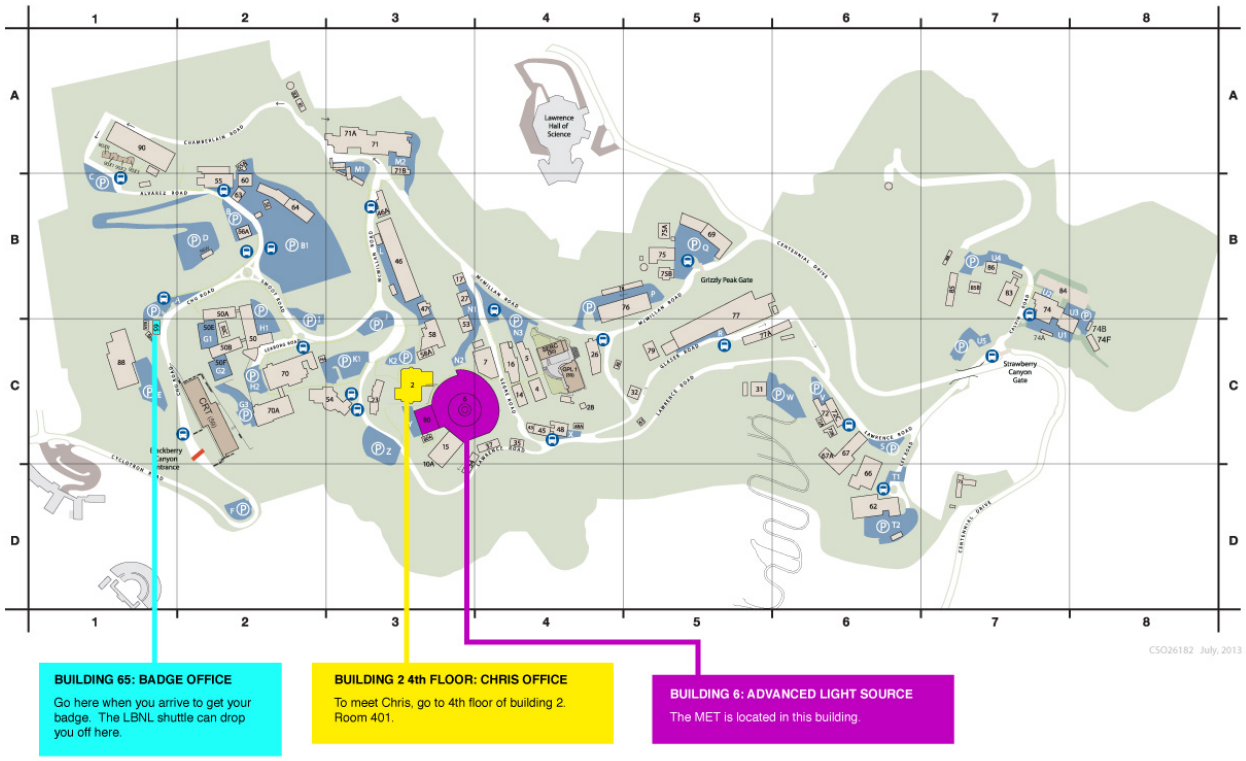
+1 (510) 486-4000

Transportation Options to LBNL

- [Official list of transportation options to LBNL from airports and transportation hubs](#).
- If you have any questions about getting to LBNL email Chris at cnanderson@lbl.gov and he can help you figure out the best option.

All transportation options require that you print your gate pass. On the Berkeley Lab shuttle, you will need to show it to the driver; for all other options you will need to show it at the front gate.

Important Locations at LBNL



- During your visit, you will go to the Badge Office (Building 65, turquoise), the Advanced Light Source (Building 6, purple) and possibly Building 2 (yellow) where the Resist Processing Lab and Chris' and Patrick's offices are located.
- The numbering of buildings on the LBL campus makes no sense and follows no logical convention. Sorry about that!
- You can walk everywhere but there are hills. You can also take LBNL campus shuttles. The people at the Badge Office can tell you where to pick up the shuttle to the ALS. Tell the shuttle driver the building you are going to and the driver will help you.

Transparency on Procedures, SOPs, and Checklists

In the spirit of transparency, here are links to operational procedures and checklists that our staff uses everyday. If you have questions about these, let us know.

- MET5 Lithography Engineer Procedures
- MET5 Process Engineer Procedures
- MET5 Tool Setup & Calibration Procedure (references MET5 Flux Calibration Procedure)
- Process Engineer Checklist
- EUVL Operations Ethos

SEM instructions, passwords, support

SEM computer login credentials (for boot-up)

- password: Hitachi

PC_SEM software login credentials

- username: metuser
- password: bmetlith

SEM instructions

Click here to view SEM instructions

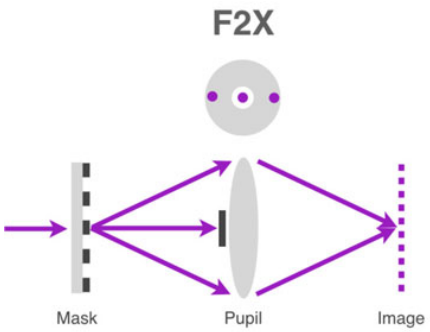
To request SEM access on a non-shift day

Email or call Chris Anderson

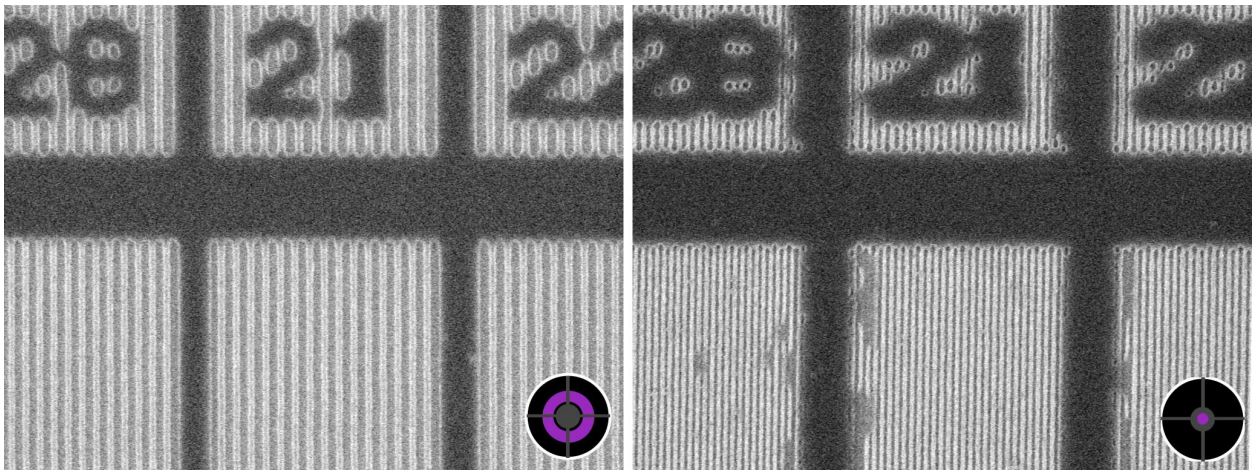
Lithography Notes

Pseudo phase-shift-mask (PSM) illumination (also called "F2X")

At SPIE 2010, we demonstrated an imaging technique called pseudo phase- shift-mask (PSM) where features get frequency doubled by because the 0-order is blocked by the MET central obscuration.



Below are SEM images of the F2X field printed with annular illumination (left) and "F2X" illumination (right). The right image has frequency-doubled content



As described above, this technique is only recommended if your resist is known to be high performing. This imaging technique has two undesirable side effects that make metrology challenging:

- Finding best focus (highest aerial image contrast) is difficult because the aerial image contrast oscillates through the z position of the wafer due to the two-beam interference mechanism that forms the image (it is different than conventional image formation).
- The z location of best aerial image contrast changes with feature size due to the small spherical aberration in the optic.
-

This imaging technique should only be used to check ultimate resolution. You will not be able to obtain process window statistics. When looking for the best image, most users capture SEM images of a particular feature size at every z position of the wafer and then pick the one that looks the best.

The best print of 14 nm 1:1 features will be at a different z position than then best print of 11 nm 1:1 features due to the spherical aberration in the optic. The spherical aberration effect is small (20 nm to 40 nm offset) but it is observable.

Also, because the zero order is blocked, this imaging technique requires about 1.8X the dose required when printing the same size feature with annular illumination. For example, if it takes a dose of 10 mJ/cm^2 to print 12 nm 1:1 lines with annular illumination. It takes a dose of about 18 mJ/cm^2 to print 12 nm 1:1 lines with the pseudo PSM imaging technique because half of the light transmitted by the mask is blocked by the central stop of the projection optic.

Resist tone (pos vs. neg) and mask tone (bright vs. dark) 2x2 imaging comparison and discussion

- Resist tone (pos vs. neg) and mask tone (bright vs. dark) 2x2 imaging comparison and discussion

Still have questions?

- The entire MET team is dedicated to making your experiment and visit the best it can be. If you still have questions, please feel free to contact us.

Changelog

2021.03.08

- Linked to EUVL Operations Ethos in Transparency on Procedures, SOPs, and Checklists
- Added rules of thumb in Productivity / How Many Wafers can I get Exposed In a Shift?

2021.02.24

- Brought the Pseudo phase-shift-mask (PSM) illumination (also called "F2X") section up to date for MET5; it was originally written with MET3 in mind.

2021.02.12

- Migrated from HTML page on met.lbl.gov to a Google Doc that gets exported as PDF so that anyone can easily make changes
- Removed all MET3 information. MET3 is being decommissioned
- Major change to language about productivity and wafer expectations per shift. This change reflects new 2021 values / culture / leadership with emphasis on prioritizing accuracy, communication, transparency, documentation and quality. We've found that trying to meet a throughput target doesn't lead to maximizing value to our customers and we are making some changes in how we work in 2021. The new Productivity / How Many Wafers can I get Exposed In a Shift… section reflects this change.
- Added two new sections How we define a successful / fulfilled shift and How we define an unsuccessful / unfulfilled shift
- Added Procedures, SOPs, and Checklists section